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Abstract. Photoabsorption by highly charged ions plays an essential role in astrophysical plasmas. Diagnostics of photoionized plasmas surrounding binary systems rely heavily on precise identification of absorption lines and on the knowledge of their cross sections and widths. Novel experiments using an electron beam ion trap, FLASH EBIT, in combination with monochromatic synchrotron radiation allow us to investigate ions in charge states hitherto out of reach. Trapped ions can be prepared in any charge state at target densities sufficient to measure absorption cross sections below 0.1 Mb. The results benchmark state-of-the-art predictions of the transitions wavelengths, widths, and absolute cross sections. Recent high resolution results on Fe^{14+}, Fe^{15+}, and Ar^{12+} at photon energies up to 1 keV are presented.

Keywords: Photoionization, highly charged ions.
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INTRODUCTION

The recent prediction [1] and discovery (see, *e. g.*, [2]) of the warm-hot intergalactic medium (WHIM) has brought the role of highly charged ions again to the center of attention. Half of the baryonic matter, hitherto unseen due to its extremely tenuous density, is accreted in humongous filamentary structures connecting groups of galaxies. In its gravitational contraction, the originally evenly spread matter heats up to temperatures of 10^5 to 10^6 K, and does not further coalesce into stars or into the galactic interstellar medium. WHIM has been detected through detailed analysis of x-ray and VUV absorption spectra using quasars as the source. The only indicators of its presence are photoabsorption lines of astronomers' *"metals"*, light and mid-heavy elements, which retain a few bound electrons even at temperatures that let the far- moreabundant hydrogen and helium disappear, at least in spectroscopic terms. Moreover, the growing number of detected black holes is now investigated by looking at x ray spectral signatures of their accretion disks and surrounding photoionized plasmas. Powerful radiation from matter heated near the event horizon pervades the neighborhood, driving the charge state of atoms to high positive charges. This has been unmistakably revealed by absorption lines of iron ions. They carve deep imprints in the blackbody x-ray spectra seen by the Earth-orbiting x-ray observatories *Chandra* and *XMM-Newton*. However, interpretation of such data remains even today hindered by deficiencies of atomic structure calculations used in the astrophysical community.

Laboratory investigations of photoionization (PI) of highly charged ions (HCIs) have been a difficult subject. Clearly, both the production of sufficient quantities of HCIs and the generation of the necessary ionizing radiation require serious experimental efforts. Solid-state studies at synchrotrons benefit from target densities which are roughly ten orders of magnitude higher than those found in gas-phase experiments. For ions, another drop of three or even more orders of magnitude in density has to be coped with.

Two methods have found application, with different variations. The first class of experiments is based on hot and dense plasmas generated either by energetic discharges or laser pulses [3,4]. These plasmas are used as a target containing the ions, which is then "backlighted" by a pulsed radiation source. Most likely this backlighter is also synchronously produced by means of the same or another discharge or laser pulse. By its nature, these techniques intrinsically imply the need for sophisticated time-resolving temperature, density, as well as spectral diagnostics of both the plasma and the light source. They allow one the investigation of PI and photoabsorption from short lived, collisionally excited initial states of the target ion species. Large lasers with pulse energies in the kJ range, or MJ electrical discharges, as in [4], are needed. The most advanced experiments have provided valuable insight into plasmas at conditions that are close to those prevailing in the interior of the Sun. Future experiments will allow for a critical evaluation of the theoretical opacity calculations in use in the Standard Solar Model, which are currently under discussion in view of observational discrepancies between estimated and measured solar abundances (cf. [5]).

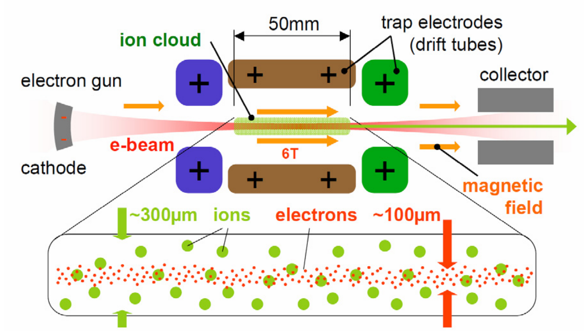

FIGURE 1. Principle of an electron beam ion trap. An electron beam is compressed by a strong magnetic field into which it is injected axially. The negative space charge of the electron beam atracts positive ions and traps them. At the same time, the electron beam produces the initial positive ions from neutrals crossing its path, and drives up the ionization of the trapped ions until the binding energy of the least bound remaining electron becomes higher than the kinetic energy of the impacting electrons. The ensemble of stored ions can be used as target for photon experiments.

The other major approach to PI of ions is the use of merged-beam techniques [6-9]. Photon and ion beams are brought to overlap over a certain interaction region, and the resulting ions are separated as a beam and detected as a function of the photon energy. Beams are always on, and long integration times compensate for the fact that ion beams are extremely tenuous, and for the reduction of photon flux resulting from the monochromatization of the radiation source. By these means, it has been possible to collect a large body of data on PI of singly charged ions. In the case of carbon, the PI of the K-shell electron at 300 eV photon energy was investigated [9]. But also a small number of experiments have been performed using multiply charged ions, with ionization potentials up to 150 eV [7,8]. Great advantages of the merged beam method are the high spectral resolution resulting from the use of intense synchrotron radiation sources in combination with advanced monochromators, its excellent selectivity, resulting of the charge-over-mass separation possible with ion beams, and absolute cross section measurements based on well established procedures. However, for higher charge states, ion beam currents become very low. The most powerful state-of-the-art electron cyclotron resonance HCI sources can deliver output beams of nearly $3\cdot10^{15}$ ions/s of O^{6+}, or $1.5\cdot10^{14}$ ions/s of Ar^{16+}. Moreover, emittance issues reduce the current available in the interaction region, and thus the ion target density. In a recent example, only 40 nA of C^{3+} reached the interaction region. These figures make for a typical areal density for singly charged ion beams in such devices of roughly 10^7 ions/cm^2, and even lower for multiply and highly charged ions. Certainly, technical improvements in those already highly sophisticated setups are likely to be implemented in future facilities, such as PIPE [10]. But the experimental effort needed will still increase disproportionately with the charge state of the HCI under investigation.

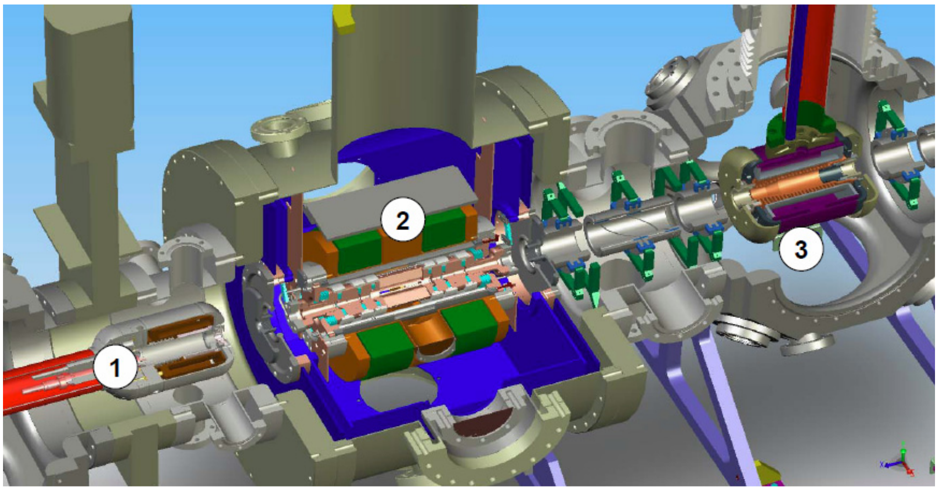

FIGURE 2. Section through the apparatus: (1) Electron gun; (2) superconducting magnet and trap electrode assembly; (3) electron collector and ion extraction optics. The photon beam enters through the collector bore and is dumped on the electron gun.

A new pathway has been recently opened with the introduction of electron beam ion traps (EBITs) as HCI targets for soft x-ray photon beams. In an EBIT (see Fig. 1), a very dense electron beam collisionally ionizes atoms and traps the ions produced simultaneously, up to bare U^{92+} and even Cf^{96+} [11]. Hundreds of experiments have been carried out using the spontaneous emission from the trapped ions in all spectral ranges from the visible to the hard x rays. The first experiment using a free-electron laser photon beam for the resonant excitation of the *2s-2p* transition in Li-like Fe^{23+} by Epp et al. [12] (see Fig. 2) demonstrated the feasibility of the novel combination and also laid out the principle for later PI experiments. Using ions stored in a Penning trap was already proposed in the 1980's and demonstrated later for low charge states [13-15]. The essential advantage of an EBIT is the target density. The ion cloud trapped in an EBIT has a cylindrical shape and typical dimensions of a few hundred microns in diameter versus several centimeters in length. In an end-on view, the integrated areal density (cf. Table 1), given by the number of trapped ions (on the order of millions to hundreds of millions) is about 10^9 to 10^{10} ions/cm^2. By superimposing the photon beam longitudinally, radiation is optimally used. One should note that the ion production and trapping efficiency of EBITs is excellent for all charge states, exception made of the highest ones in heavy elements.

TABLE 1. Estimated areal densities for some of the ions investigated in this work (for the ion Xe^{44+} only extrapolated) for a trapped ion cloud of 250 µm diameter and 50 mm length.

Ion species	I_{beam} (mA)	$E_{electron}$ (eV)	ρ_{ion} (10^{10} ions/cm^2)
N^{3+}	2.0	50	2.0
Ar^{8+}	8.0	400	1.4
Fe^{14+}	6.6	445	0.17
Fe^{23+}	300	4500	1.8
Xe^{44+}	400	10000	0.35

EXPERIMENTAL METHOD

For the present measurements we have deployed the transportable FLASH EBIT, which has already been described in [12]. Basically, the apparatus consists of an electron gun capable of delivering beams up to 500 mA, a superconducting 6 T magnet containing a cryogenic drift tube assembly, and an electron collector with a central bore through which photon beams are introduced axially into the trap region (see Fig. 2). The trap region itself is 50 mm long and located within a central drift tube with slotted apertures offering optical access to the trapped ion ensemble. Spectroscopic and optical diagnostic instrumentation is arranged radially. Furthermore, the ion inventory can be extracted in both pulsed and continuous modes through the collector aperture and deflected to a beamline at 90° from the photon and electron beam axis as shown in Fig. 3. This extraction beamline includes a Wien-type velocity filter for charge-to-mass separation of the ion beam, and a position sensitive detector with single ion sensitivity. Detailed descriptions are given in [16-18].

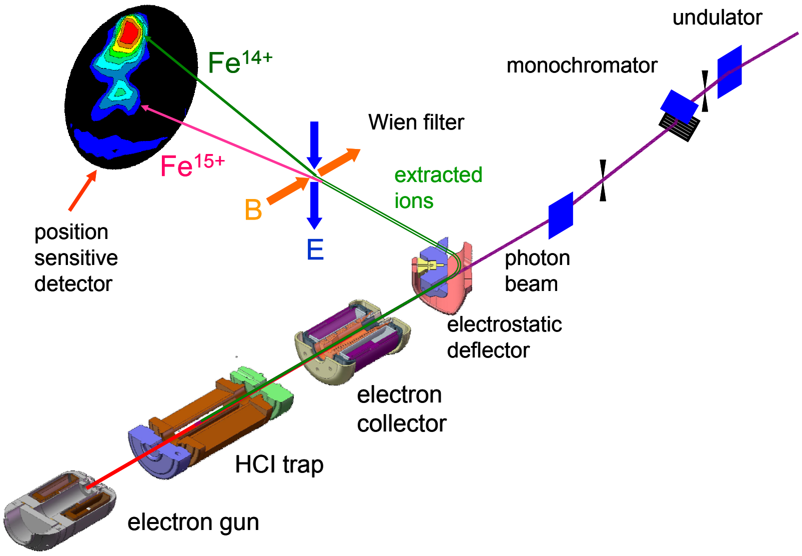

FIGURE 3. Principle of the PI measurements using an electron beam ion trap. A photon beam enters the trap through apertures in an electrostatic deflector, and overlaps with the stored ions. Extraction occurs after a suitable interaction time. Potentials at the gun and trap electrodes determine electron energy and charge state of the trapped ions, and kinetic energy of the extracted ions. Charge states are separated by a velocity filter. The photoion yield is measured as a function of the photon beam energy.

MEASUREMENTS

The first experiments were carried out at a VUV beamline at BESSY II. The comparatively low photon energy of the beamline forced us to perform testing using N^{3+} ions, the ion with the lowest ionization potential ever studied in an EBIT. To exclude the production of N^{4+} by the electron beam, its energy had to be very low (around 55 eV). A pulsed extraction scheme was needed to guarantee kinetic energies (300 eV/q) of the extracted ions which were high enough for the ion beam transport to the detector arrangement. The results with N^{3+} (cf. [16]) confirmed the suitability of the method and were in good agreement with data obtained by the merged-beam method.

In a second beamtime, FLASH EBIT was coupled to a BESSY II soft x-ray beamline, and ions such as $Ar^{8+,12+}$, Fe^{12+} and up to Fe^{14+} (see Fig. 4) were investigated [16-18] at photon energies from 400 to 1250 eV. Strong resonances in the region from 800 eV to 1040 eV were investigated in detail and with very good resolution [18]. The interaction time dependent yield of Fe^{15+} photoions was used to determine absolute PI resonance strengths and thus cross sections, based solely in the ionization probability for a single ion as a function of the integrated photon flux at a given photon energy.

Recently, a Fe^{15+} ion target was studied in this energy range; the data are still under analysis. Within the region of main astrophysical interest, photon excited autoionizing resonances coexist for this ion with others for which photon emission is the dominant decay channel. These predictions were confirmed by our preliminary data evaluation.

In general, we found excellent agreement at the level of a fraction of 1 eV for the Fe HCI with relativistic many-body perturbation theory calculations by Gu [19], a slightly worse agreement with MCDF calculations of our group [18], and much larger discrepancies with all other theoretical models. Previous plasma outflows of active galactic nuclei velocity determinations by the Doppler shift of these lines turned out to be incorrect due to the use of inaccurate predictions; our experimental confirmation of Gu's [19] predicted values has solved this conundrum.

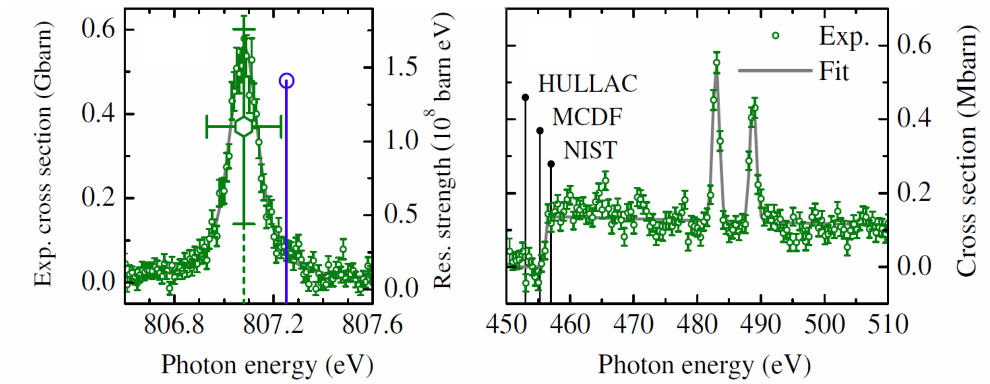

FIGURE 4. Left. Photoionization resonance (left) and edge (right) of Fe^{14+} (cf. [18]).

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